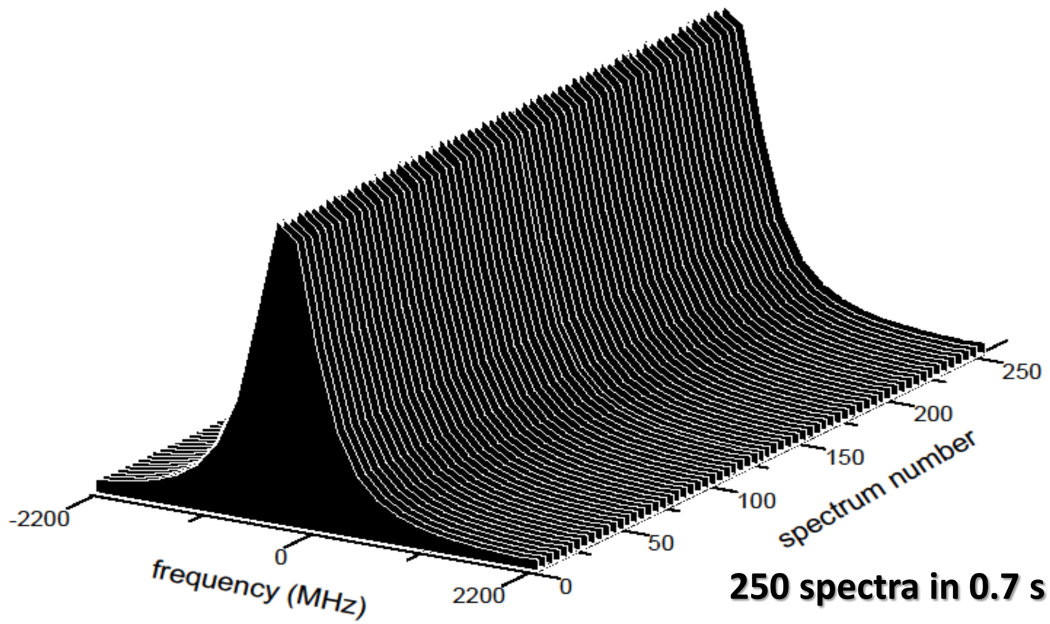
Sensor Development: Metrology Tools for Climate Science



250 spectra in 0.7 s

David A. Long

Adam J. Fleisher, Zachary D. Reed, and Joseph T. Hodges

Greenhouse Gas and Climate Science Measurements Seminar

1 August 2014

National Institute of Standards and Technology • U.S. Department of Commerce

Our approach

- **Both *in situ* monitoring and remote sensing require cutting-edge spectroscopic measurements**

- **We develop novel techniques which allow for enhanced:**
  - **Spectral coverage**
  - **Portability**
  - **Sensitivity**
  - **Accuracy**
  - **Speed**
  - **Selectivity**

Outline

- A series of new spectroscopic techniques
  - They offer a range of complexity, speed, and sensitivity

- Specifically I will discuss:
  - Photoacoustic sensor
  - Ultrasensitive cavity ring-down instruments
  - Multiplexed detection with optical frequency combs

NIST photoacoustic sensor

- Designed for routine monitoring of CO_2 concentrations
- Will be placed on the top of the Admin. Building at NIST (101).

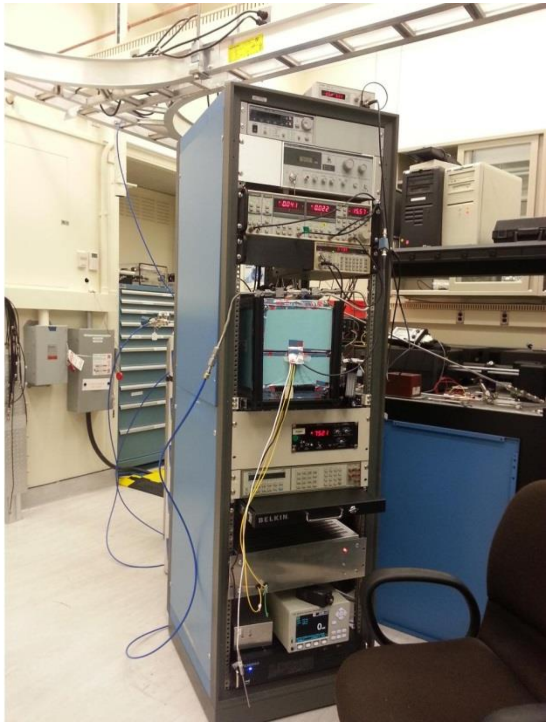
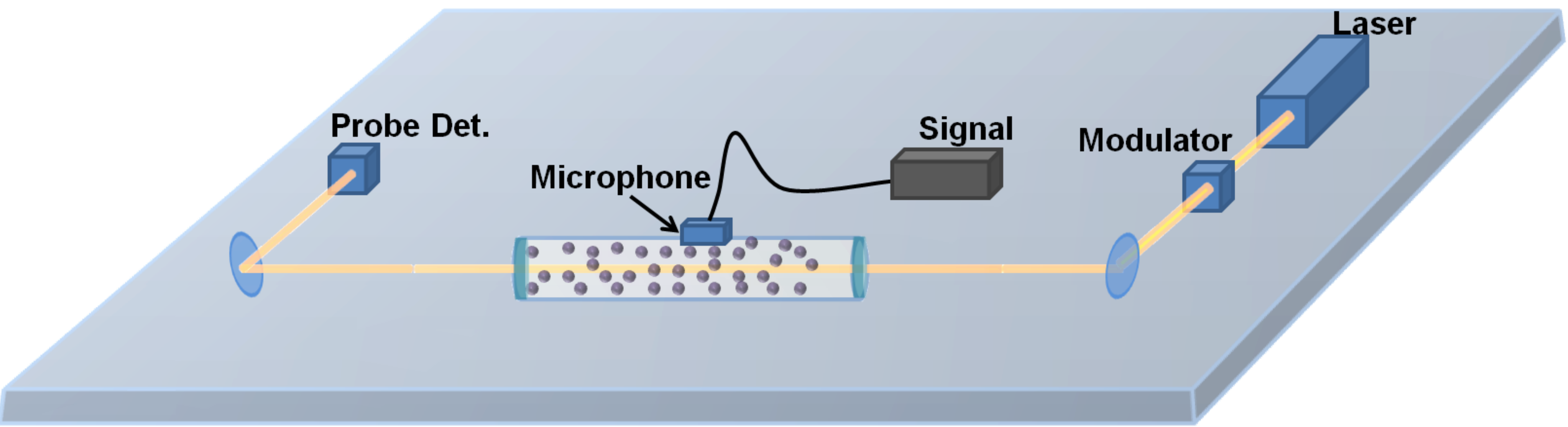


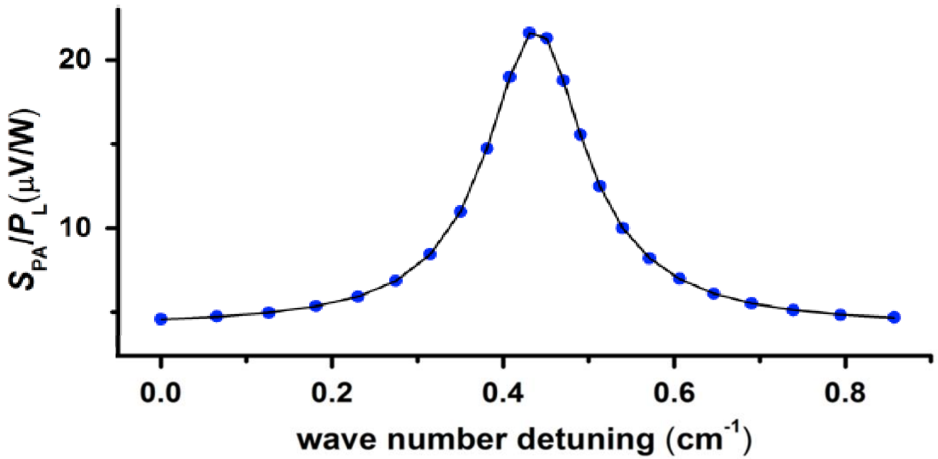
Figure from HDR Architecture, Inc.

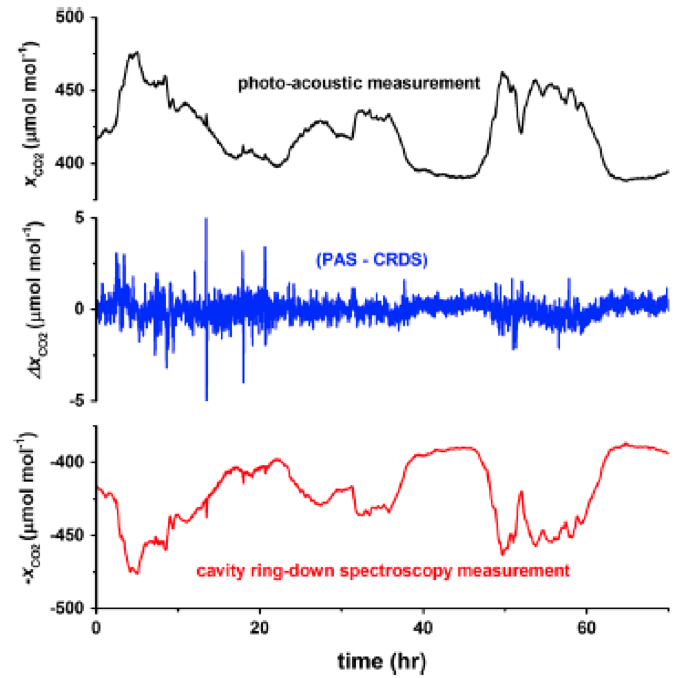
Photoacoustic spectroscopy (PAS)



- Zero background
- Optically broadband
- Relatively easy to implement
- High sensitivity
  - signal scales with laser power
- Wide dynamic range

Photoacoustic spectrometer at 1.6 μm

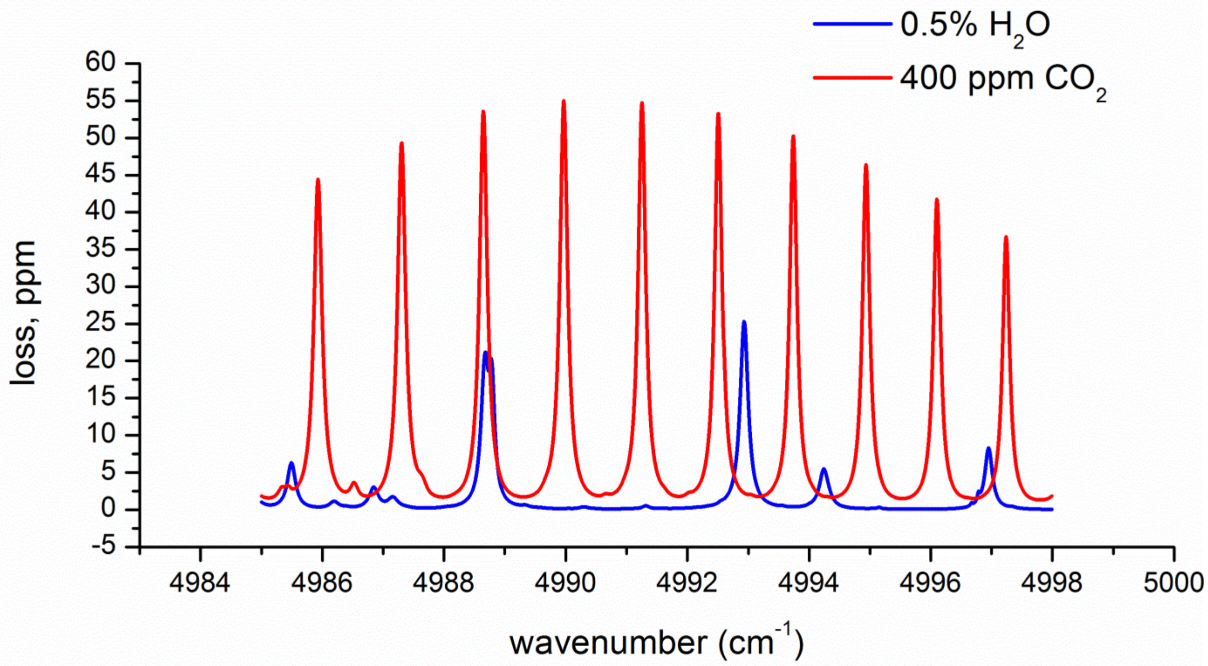




- **Allows for routine, automated measurements of ambient CO_2**
- **Uncertainty of only 0.8 ppm (0.2%)**

Z. D. Reed et al., Appl. Phys. B, (2014).
K. A. Gillis, D. K. Havey, J. T. Hodges, US Patent Pending.

New 2 µm sensor



- **Moved to 2 µm to probe stronger CO_2 transitions**
  - **Able to utilize recently developed laser technology**

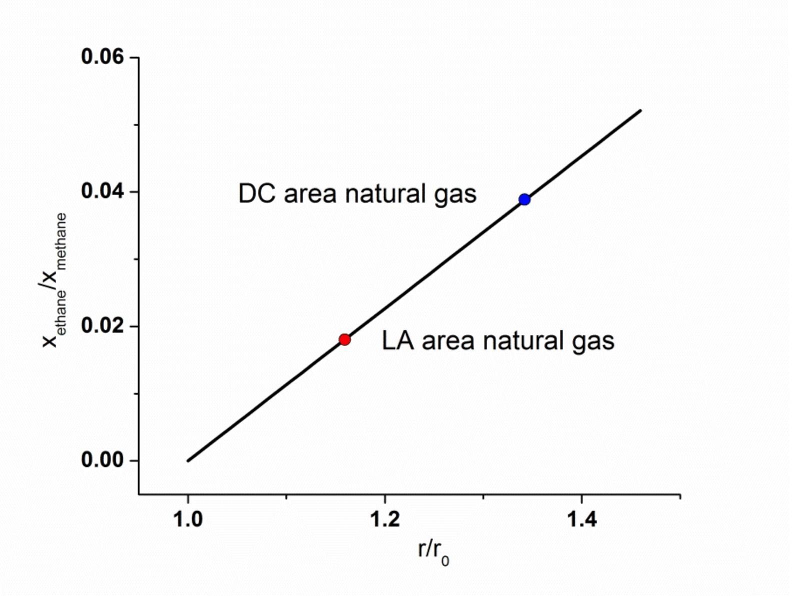
- **Signal-to-noise ratios of ~14,000:1 for CO_2 at ambient levels**

- **Allows for simultaneous humidity measurements with the same laser**

Future directions for the PAS instruments

- **Dual species PAS instrument**
  - **Use fiber switches to probe numerous species simultaneously**
  - **Potential targets include $CO_{2,}$ H_2O, NH_3, and CH_4(and their isotopologues)**

- **Mid-infrared PAS**
  - **Would allow us to probe CH_4 and C_2H_6 simultaneously**
  - **Allows for source attribution of CH_4 emissions**

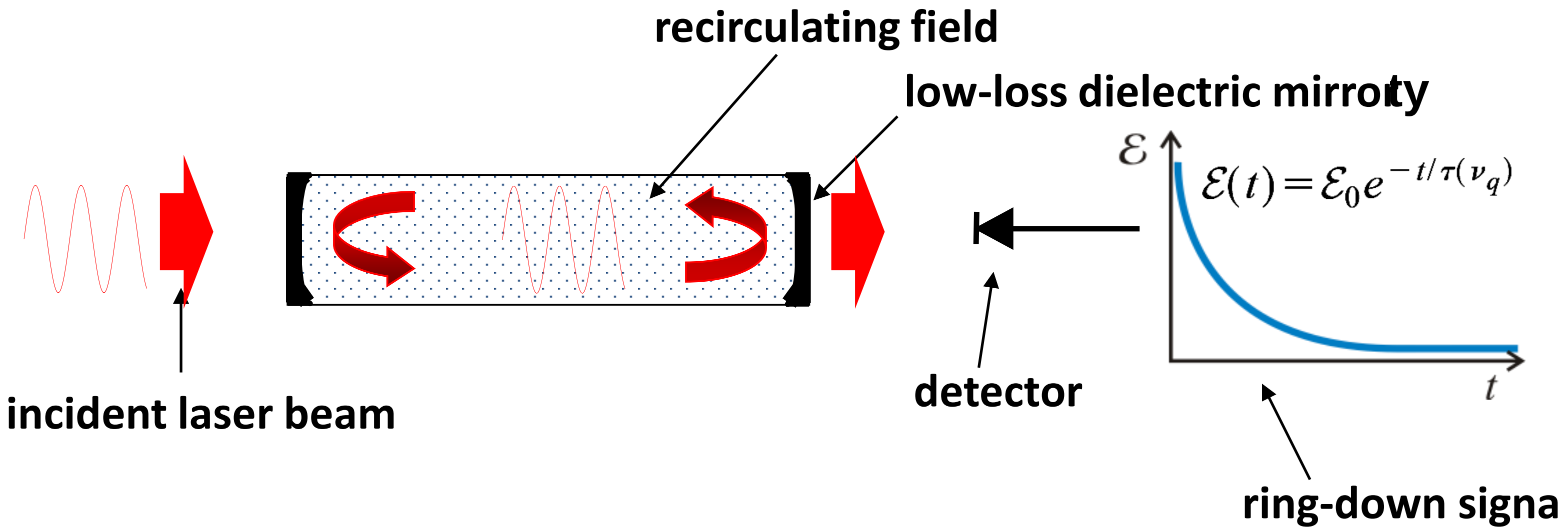


Outline

- **A series of new spectroscopic techniques**
  - **They offer a range of complexity, speed, and sensitivity**

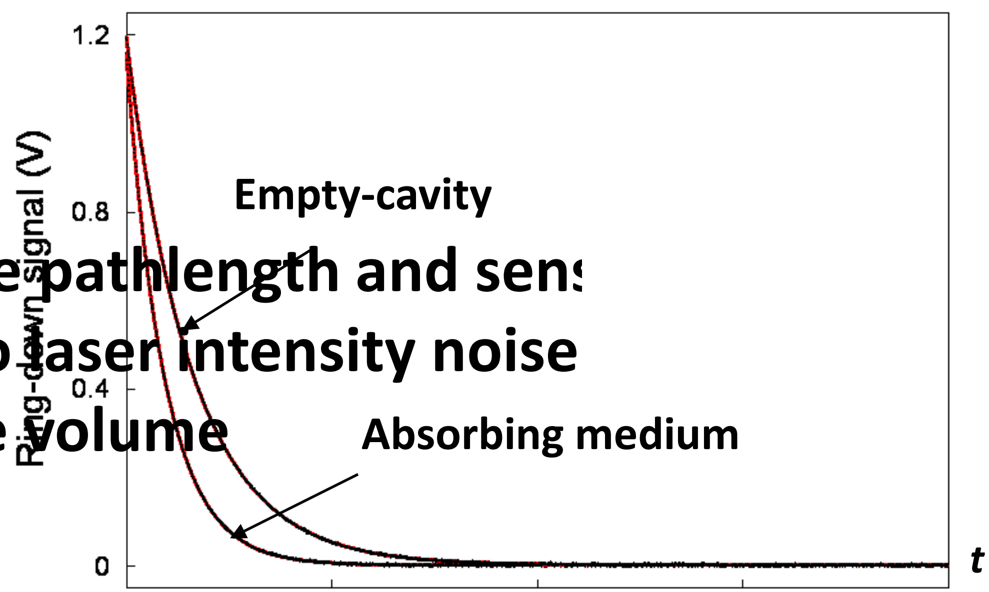
- **Specifically I will discuss:**
  - **Photoacoustic sensor**
  - **Ultrasensitive cavity ring-down instruments**
  - **Multiplexed detection with optical frequency combs**

Cavity ring-down spectroscopy (CRDS)



Advantages:

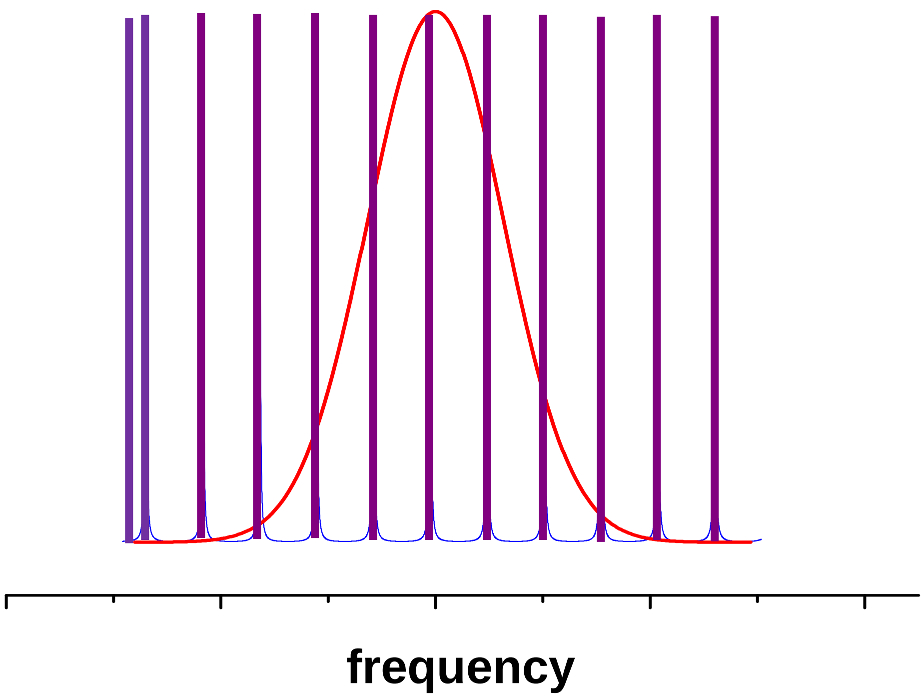
- High effective pathlength and sens
- Insensitive to laser intensity noise
- Small sample volume



The problem

- To record a spectrum you need to tune the laser frequency
- This generally requires thermal or mechanical tuning
  - This is usually non-linear and very slow

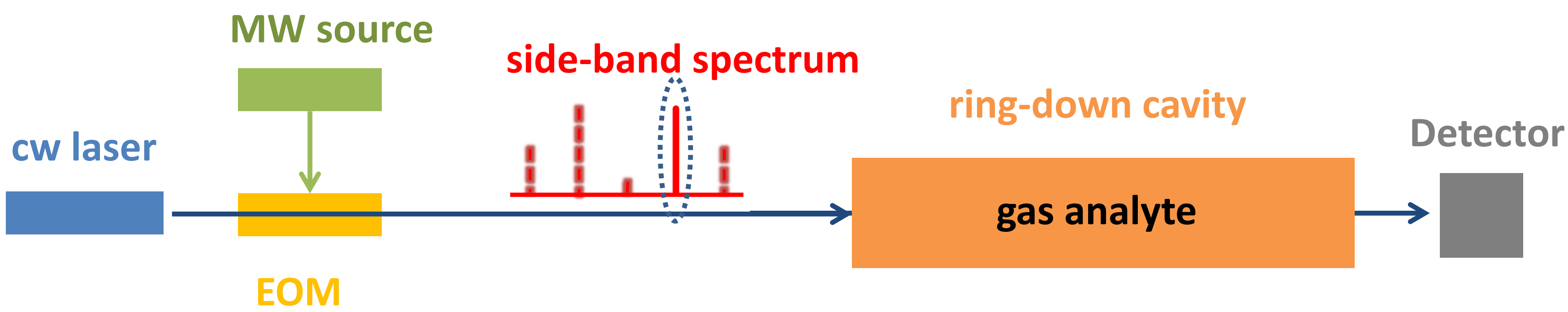
- Things are even more difficult with cavity-enhanced spectroscopy (discrete frequencies)



Frequency-agile, rapid scanning (FARS) spectroscopy

Method:

- Use waveguide electro-optic phase-modulator (EOM) to generate tunable sidebands
- Drive PM with a rapidly-switchable microwave (MW) source
- Fix carrier and use ring-down cavity to filter out all but one selected side band

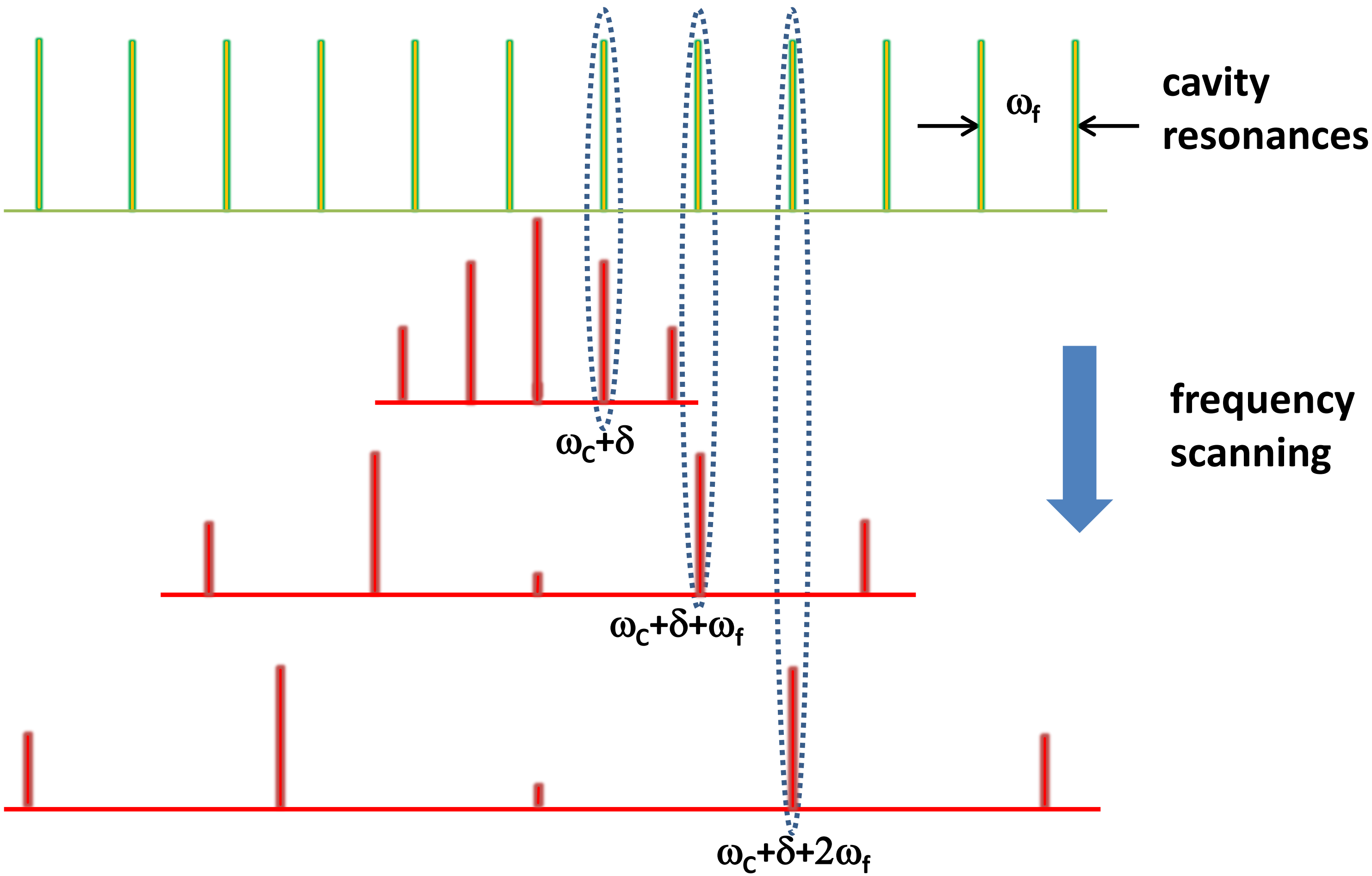


Advantages:

- Overcomes slow mechanical and thermal scanning
- Links optical detuning axis link to radio-frequency (RF) standards
- Wide frequency tuning range (> 130 GHz = 4.3 cm^{-1})

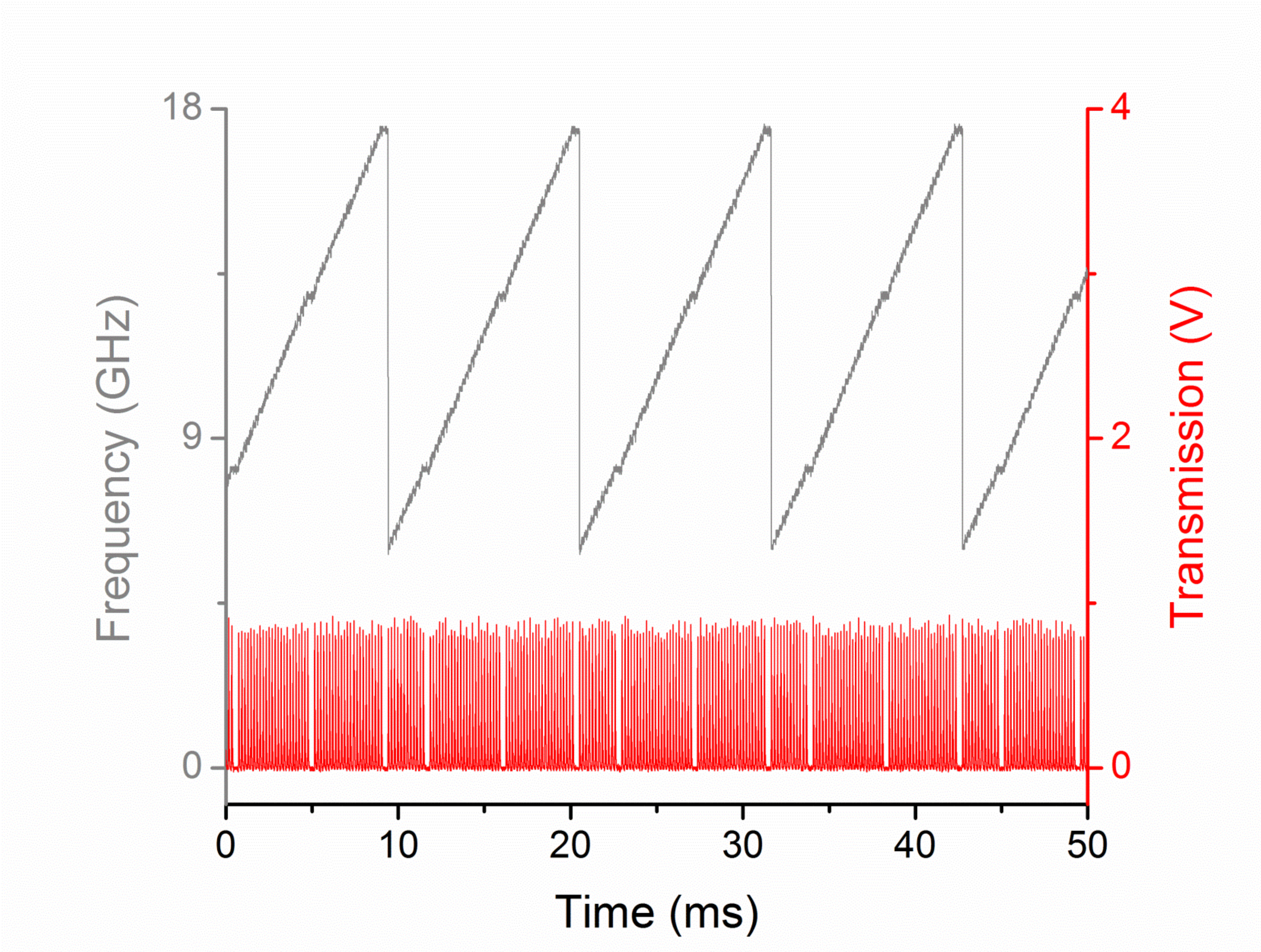
G.-W. Truong et al., Nature Photonics, (2013).
D. F. Plusquellic, et al., US Patent US20130228688 A1 (2013).

FARS operating principle

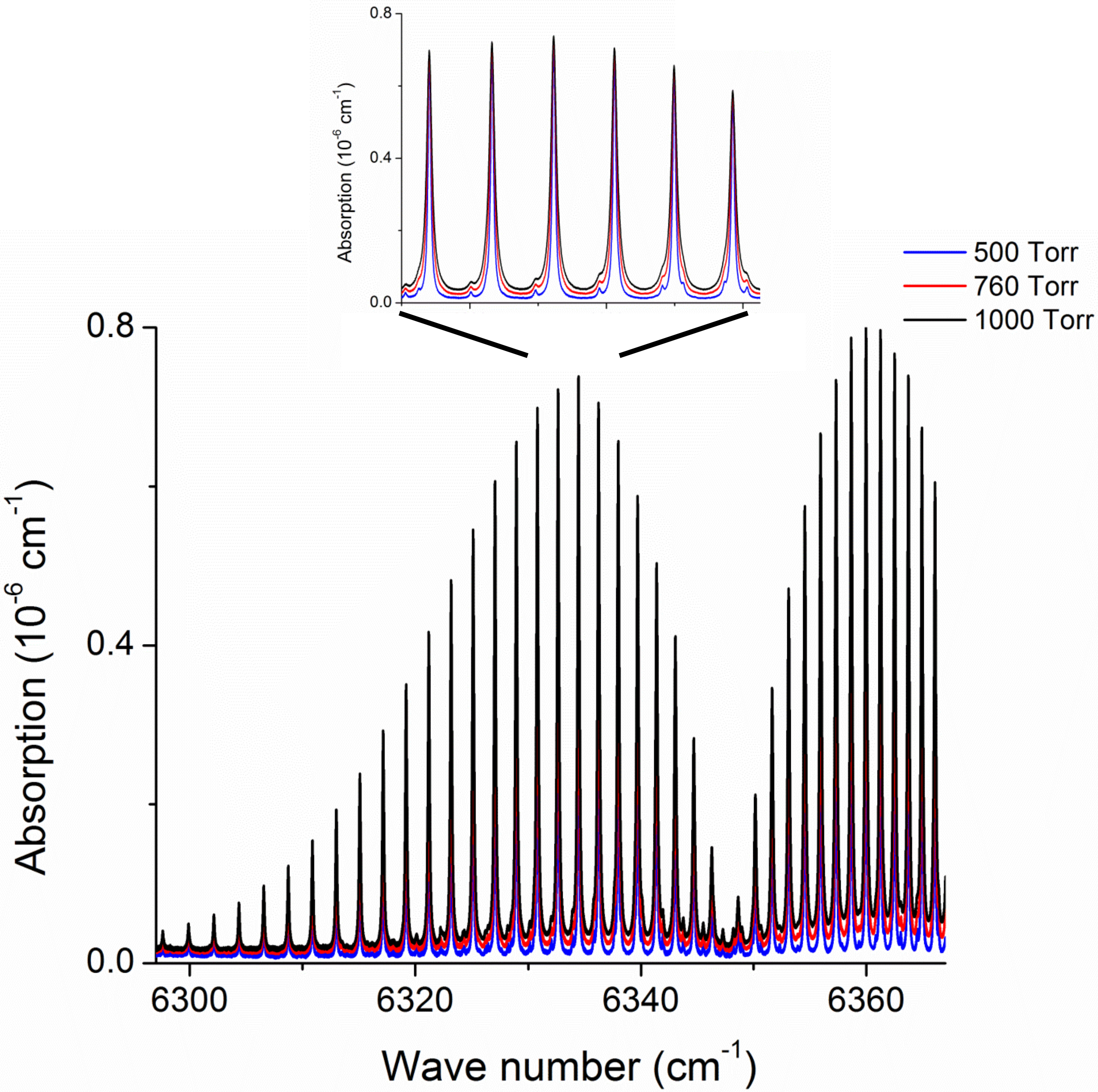


G.-W. Truong et al., Nature Photonics, (2013).

Very high acquisition rates: scanning



Spectra of entire absorption bands



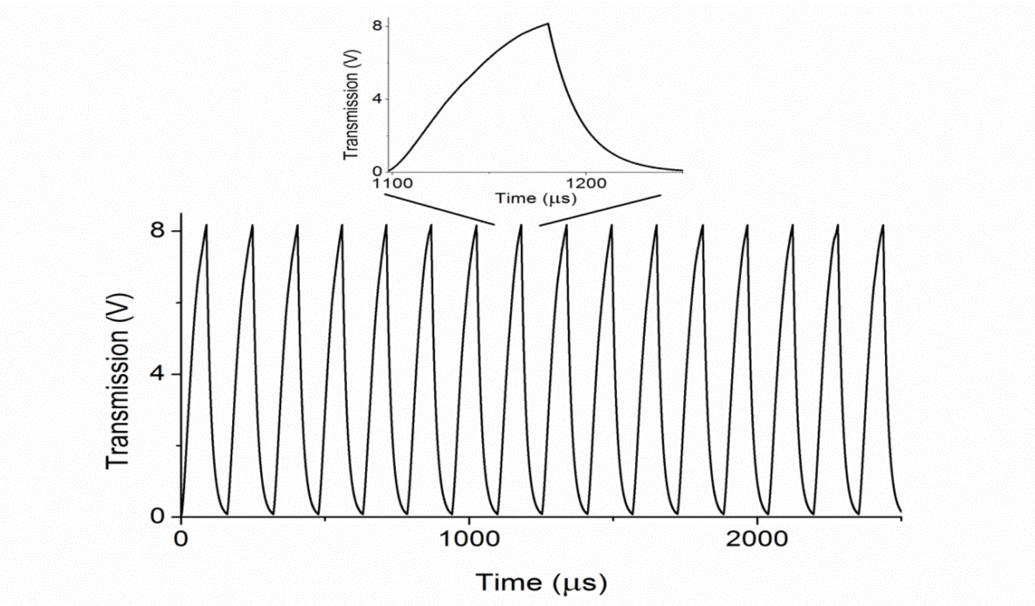
2 THz wide spectra recorded in 45 minutes

425 ppm of CO_2 in air

ECDL grating moved every 12 GHz

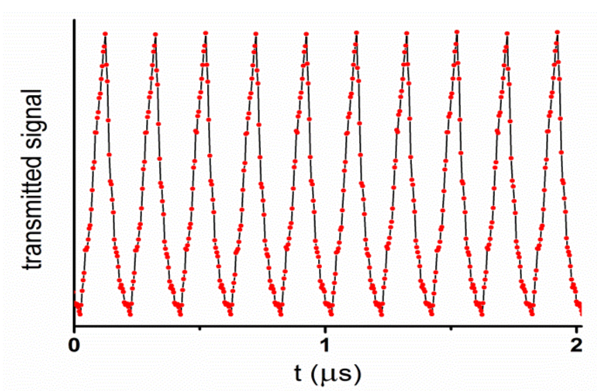
Each point is the average of 100 RDs

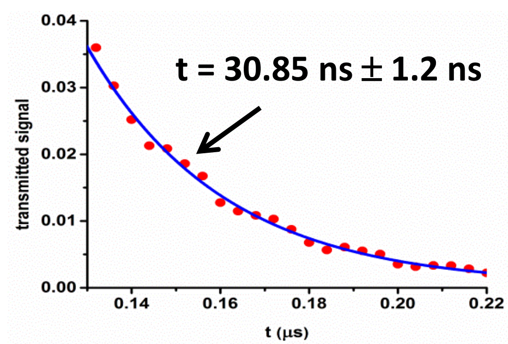
Lower finesse = faster rates



Finesse = 20,000
RD acq. rate = 8 kHz
σ_τ/τ = 0.008 %

NEA = 1.7×10^{-12} cm^{-1} Hz$^{-1/2}$





Finesse = 60
RD acq. rate = 5 MHz
σ_τ/τ = 4 %

NEA = 1.9×10^{-8} cm^{-1} Hz$^{-1/2}$

D. A. Long et al., Appl. Phys. B, (2013)
K. O. Douglass, JOSA B, (2013)

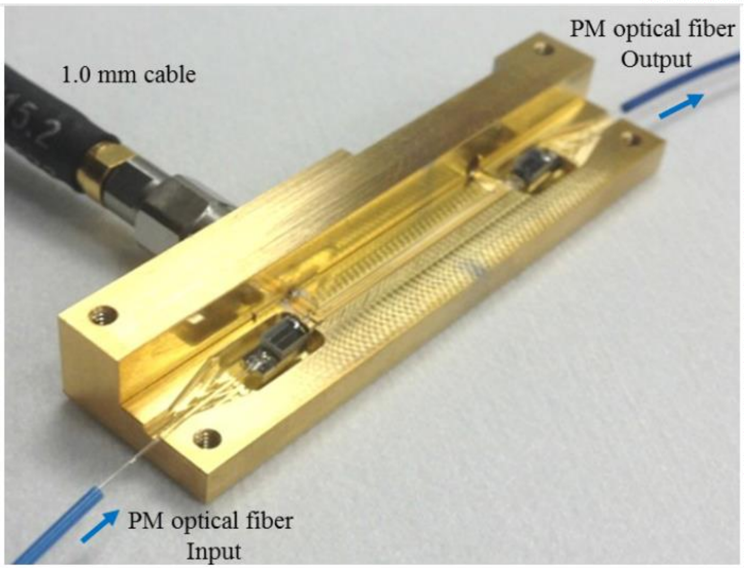
What if I want to scan faster?

- Entirely limited by the slow grating tuning

- So use higher bandwidth EOMs to reduce the number of grating steps

Even faster rates

Use recently developed W-band modulators (bandwidth up to 300 GHz!)



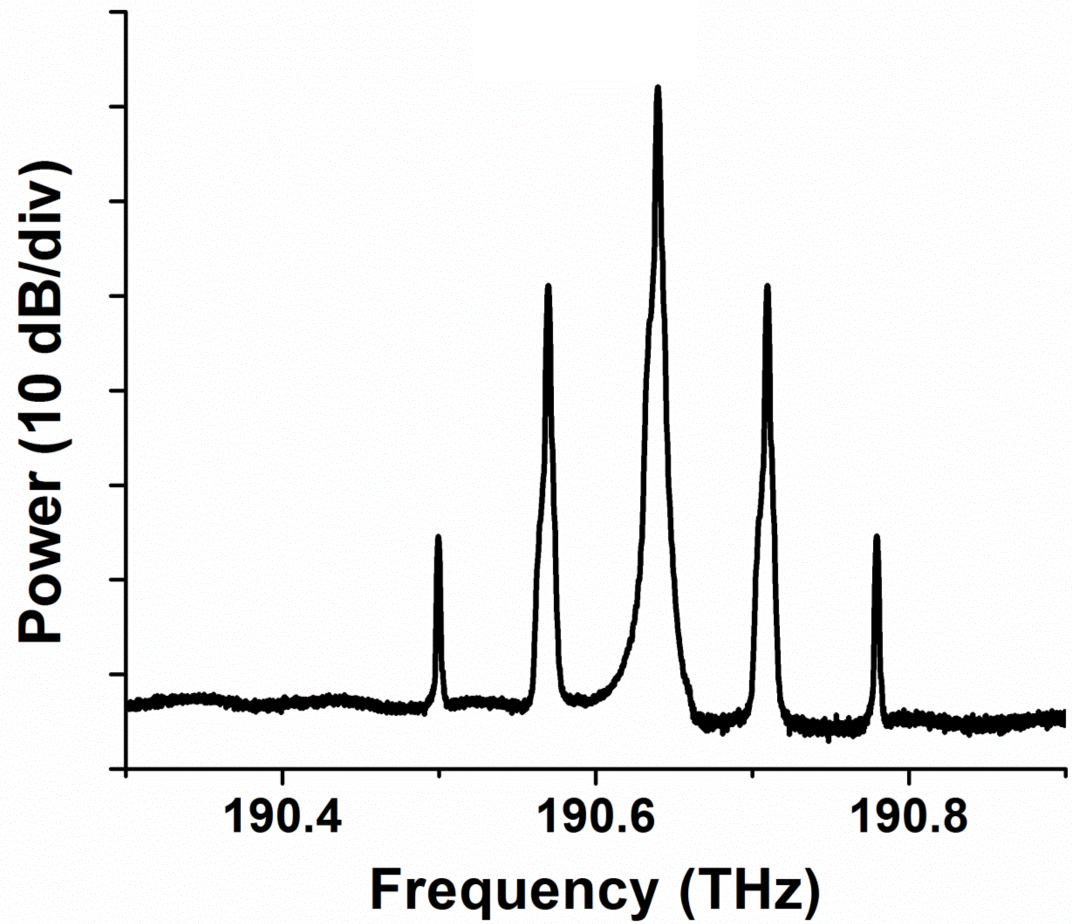
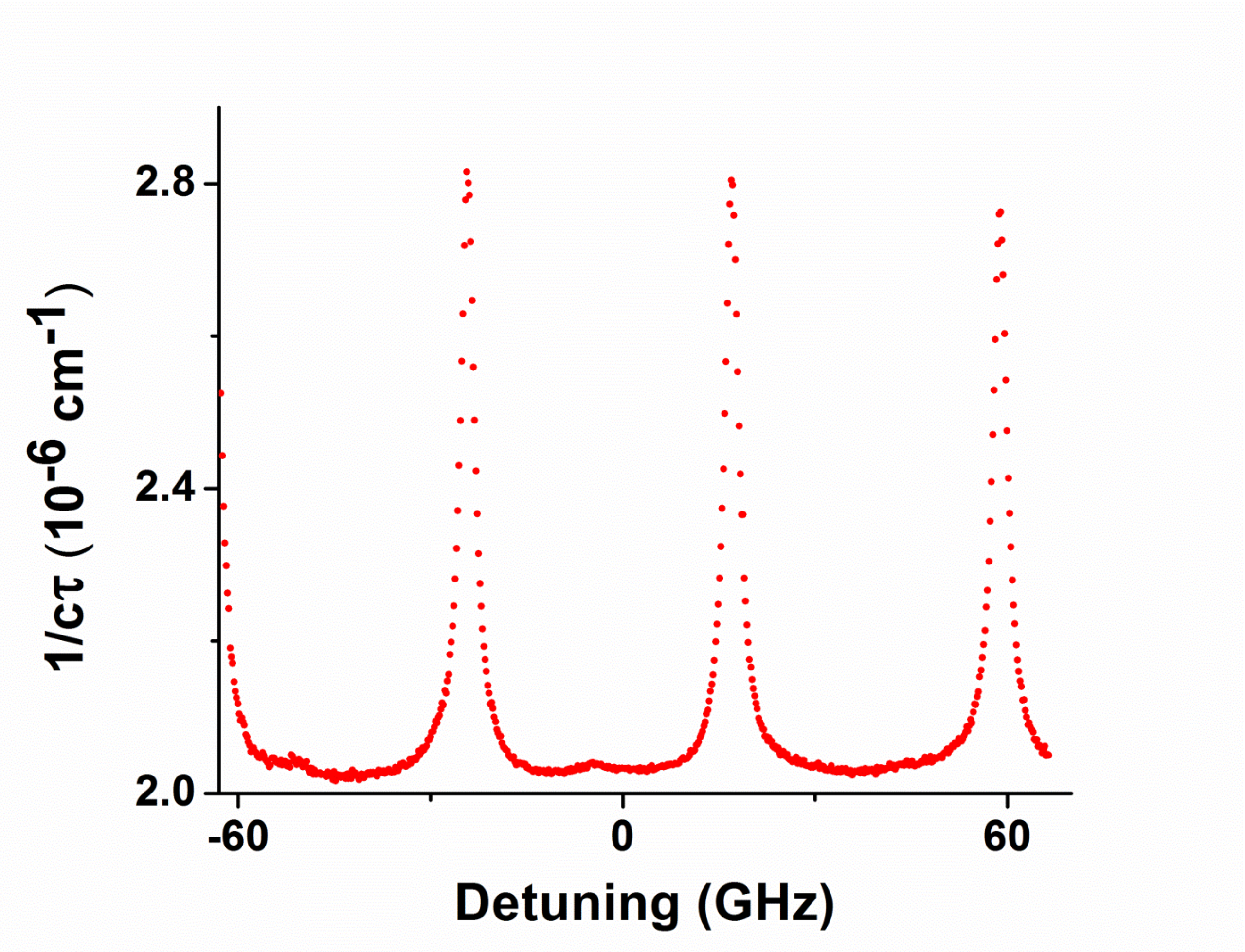


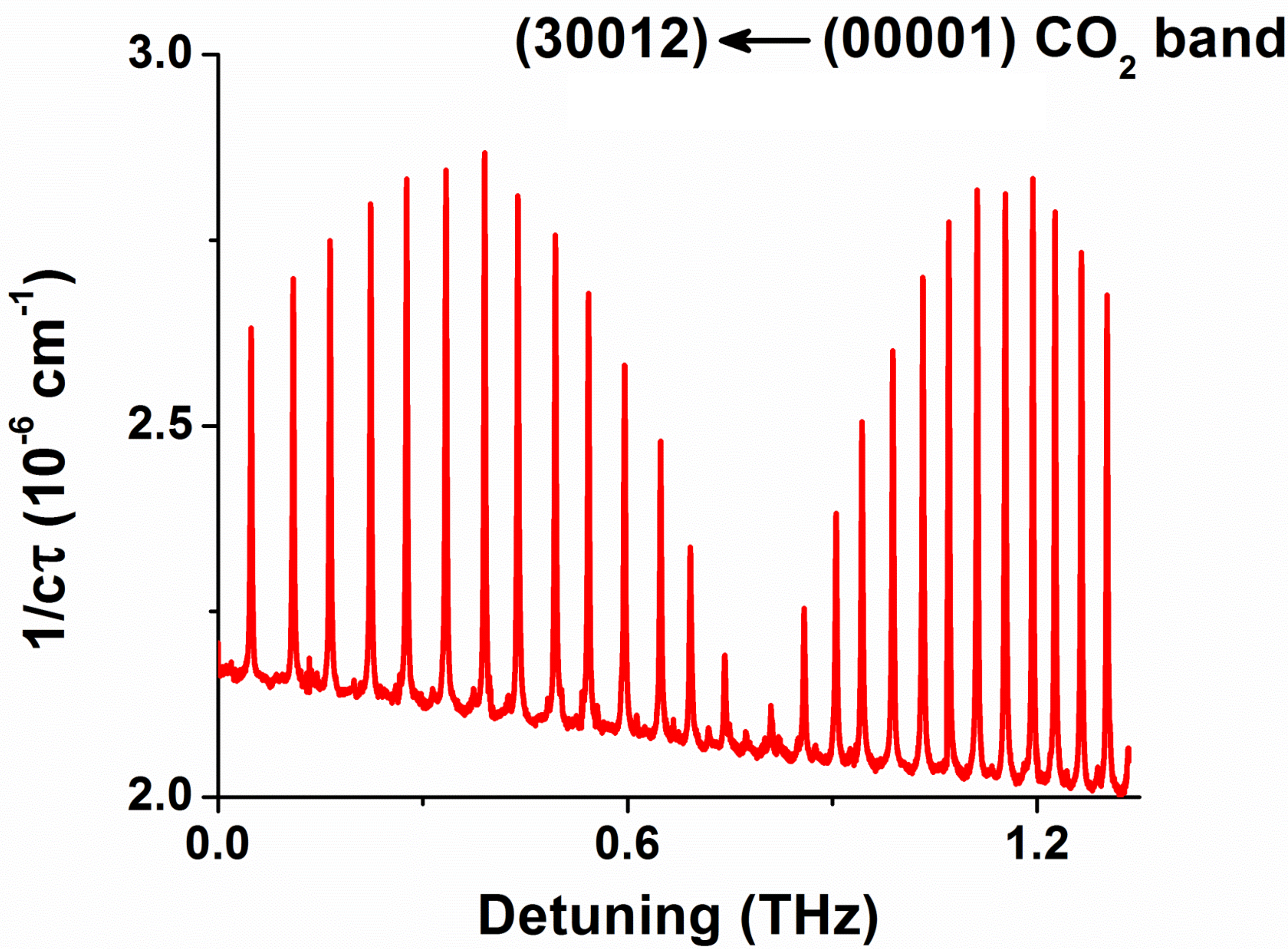
Image from Phase Sensitive Innovations

Even faster rates: single grating position

Allows for a 130 GHz (4.3 cm^{-1}) to be recorded in 3 s.



Even faster rates: grating tuning



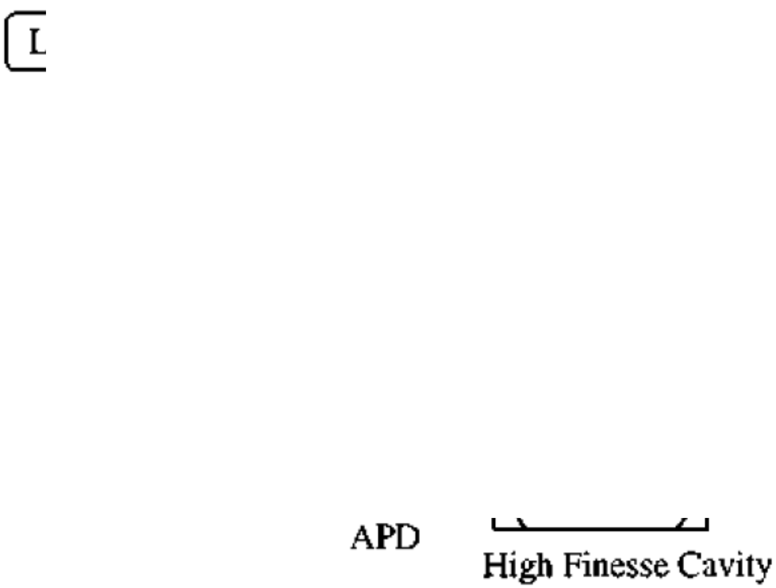
What if I want higher sensitivity?

- **To reduce $1/f$ noise, we want to make the measurement away from DC**

- **Also need to rapidly compare ring-down time constants at different wavelengths**

Improving the sensitivity: Heterodyne measurements

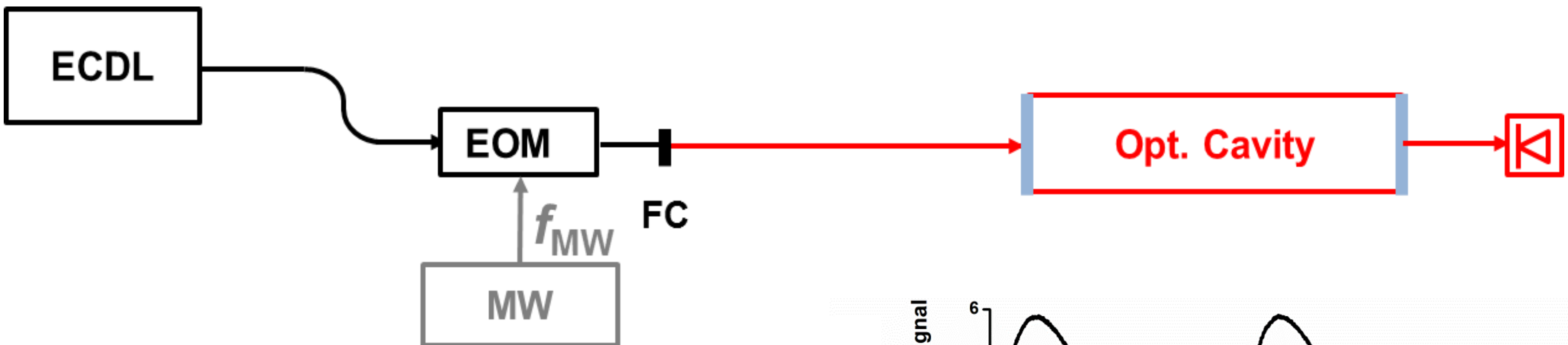
- **To do this we adapted the approach of Ye and Hall**

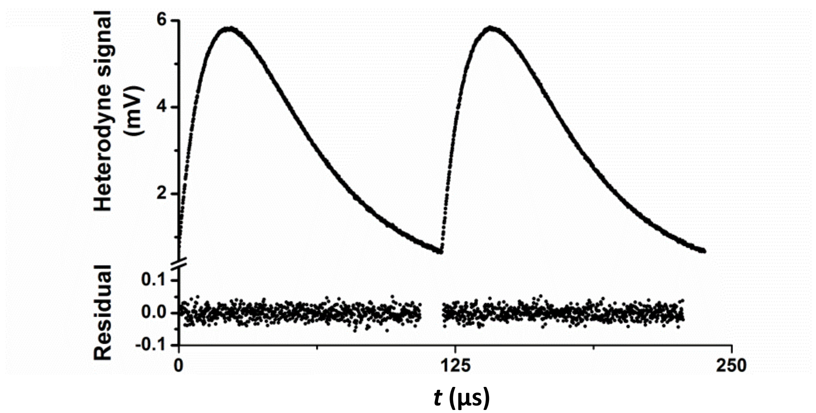


J. Ye and J. Hall., Phys. Rev. A, (2000)

Heterodyne measurements: Our approach

- Replace their two AOMs with a single EOM
- This reduces the complexity and enables rapid scanning

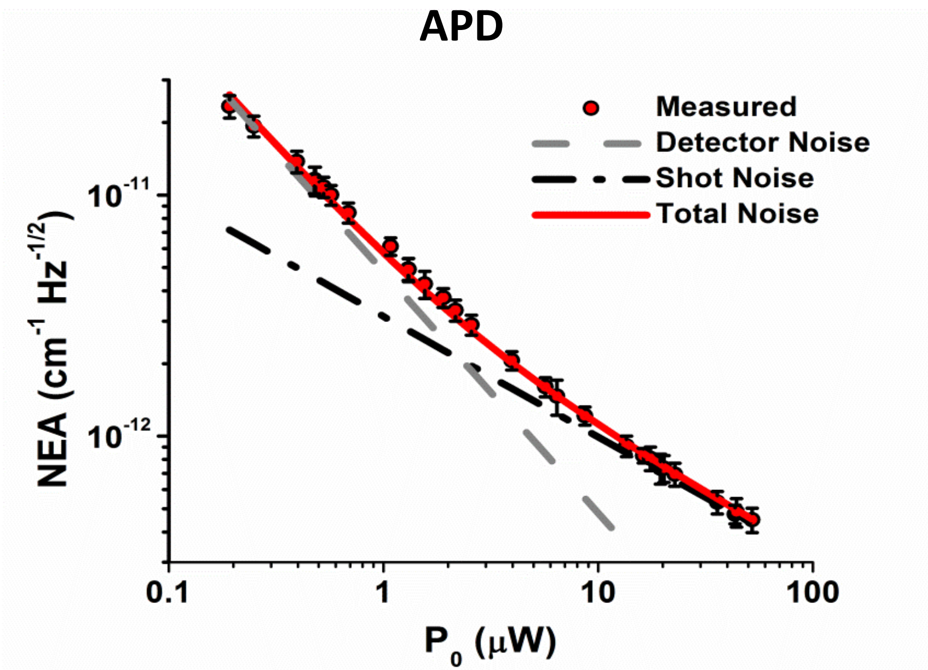


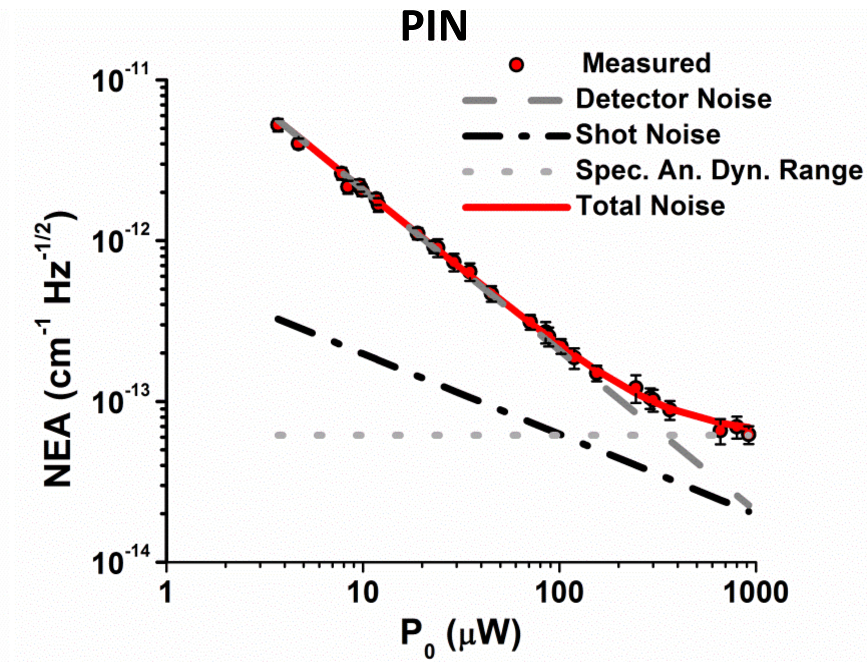


D. A. Long, et al., Appl. Phys. B, Under Review (2014)

Heterodyne measurements: Reaching the quantum-noise limit

- Utilized both a traditional InGaAs detector and an APD
- Able to reach the quantum-noise limit with the APD
- The traditional InGaAs allows for an NEA of 6E-14 cm^{-1} $Hz^{-1/2}$





D. A. Long, et al., Appl. Phys. B, Under Review (2014)

Most sensitive spectrometers

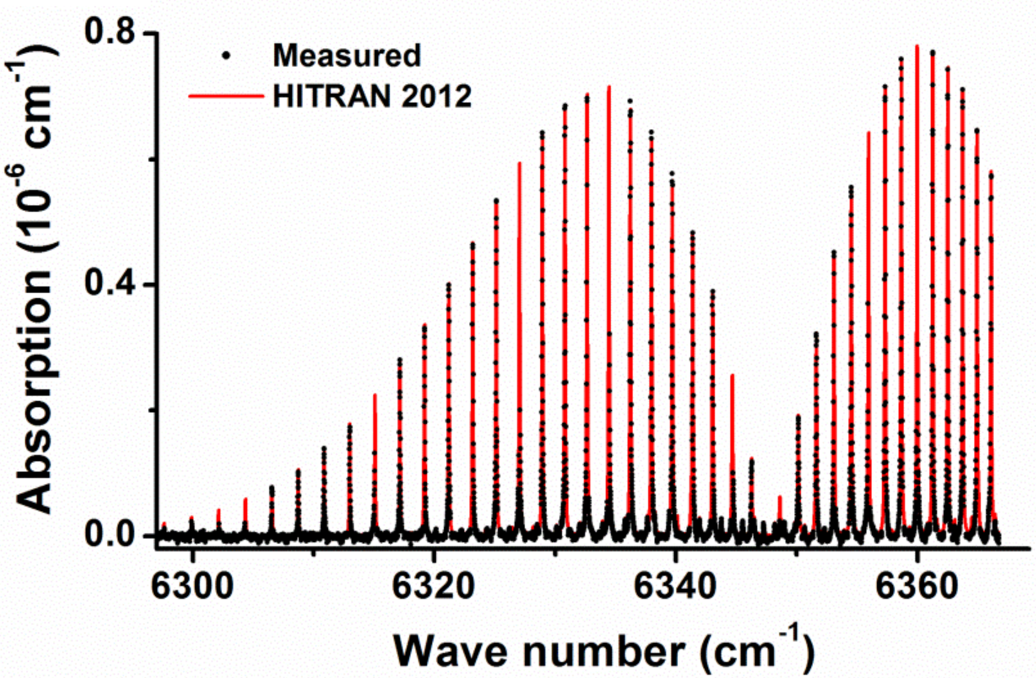
Technique	Ref.	Sensitivity (cm^{-1} Hz$^{-1/2}$)	Laser	Tuning range (nm)
NICE-OHMS	Ye et al.	**<u>1E-14</u>**	cw-Nd:YAG	**0.1**
HD-CRDS	Long et al.	**<u>6E-14</u>**	ECDL	**60**
HD-CRDS	Ye and Hall	**3E-13**	cw-Yb:YAG	**~0.5**
CRDS	Spence et al.	**1E-12**	cw-Nd:YAG	**0.14**
FARS-CRDS	Long et al.	**2E-12**	ECDL	**60**
NICE-OHMS	Ehlers et al.	**6E-12**	Fiber laser	**1**

D. A. Long, et al., Appl. Phys. B, Under Review (2014)

D. A. Long et al., Appl. Phys. B, (2013)

Heterodyne measurements: Rapid scanning

- Able to record a 26 GHz-wide spectrum in 17 ms with 50 GS/s AWG
- Observed a weak CO_2 hot band transition (3.5E-25 cm molec.$^{-1}$) in an air sample



D. A. Long, et al., Appl. Phys. B, Under Review (2014)

Outline

- A series of new spectroscopic techniques
  - They offer a range of complexity, speed, and sensitivity

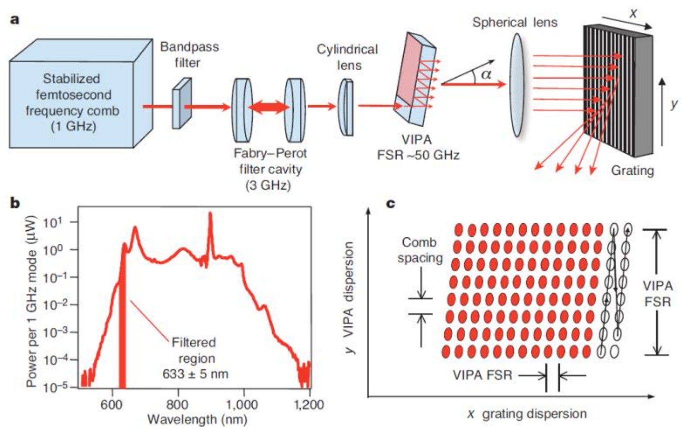
- Specifically I will discuss:
  - Photoacoustic sensor
  - Ultrasensitive cavity ring-down instruments
  - Multiplexed detection with optical frequency combs

What if I don’t want to scan?

- **Then multiplex!**

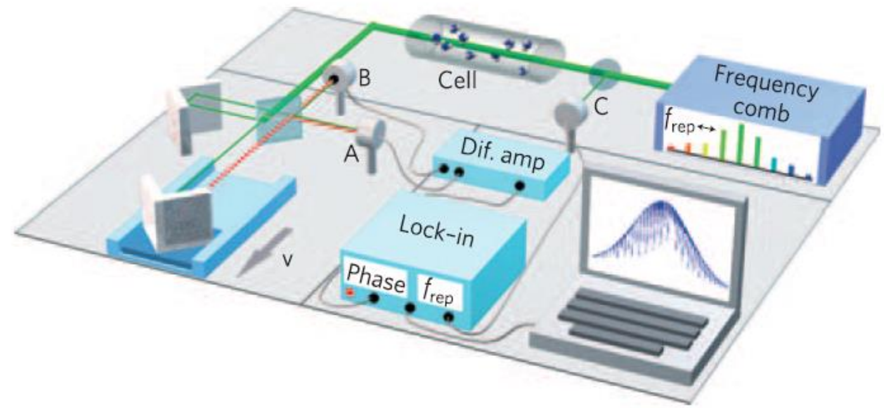
Multiplexed measurements: OFCs

OFCs have been used with a variety of detection schemes for spectroscopic measurements



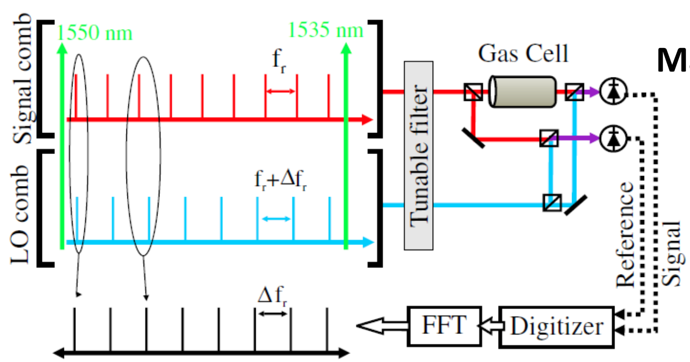
Dispersive (VIPA)

Diddams, et al., Nature (2007)



Fourier Transform

Mandon, et al., Nat. Photonics (2009)



Multiheterodyne

Coddington, et al., Phys. Rev. Lett. (2008)

Mode-locked femtosecond OFCs

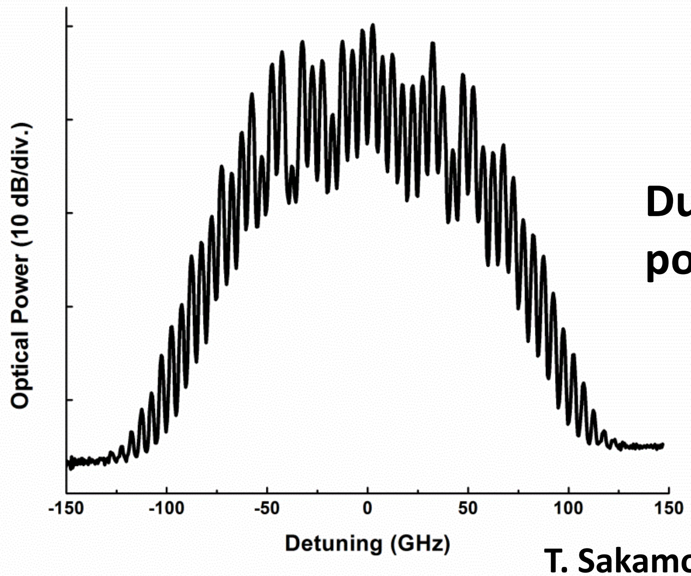
Advantages:
- Wide bandwidth (octave-spanning)
- Can be self-referenced (absolute freq. axis)

Disadvantages:
- Essentially fixed repetition rate
- Low power per tooth (nW to µW)
- Large and expensive

Image from Menlo Systems

An alternate approach: electro-optic modulators

Ideal for targeted measurements of selected species

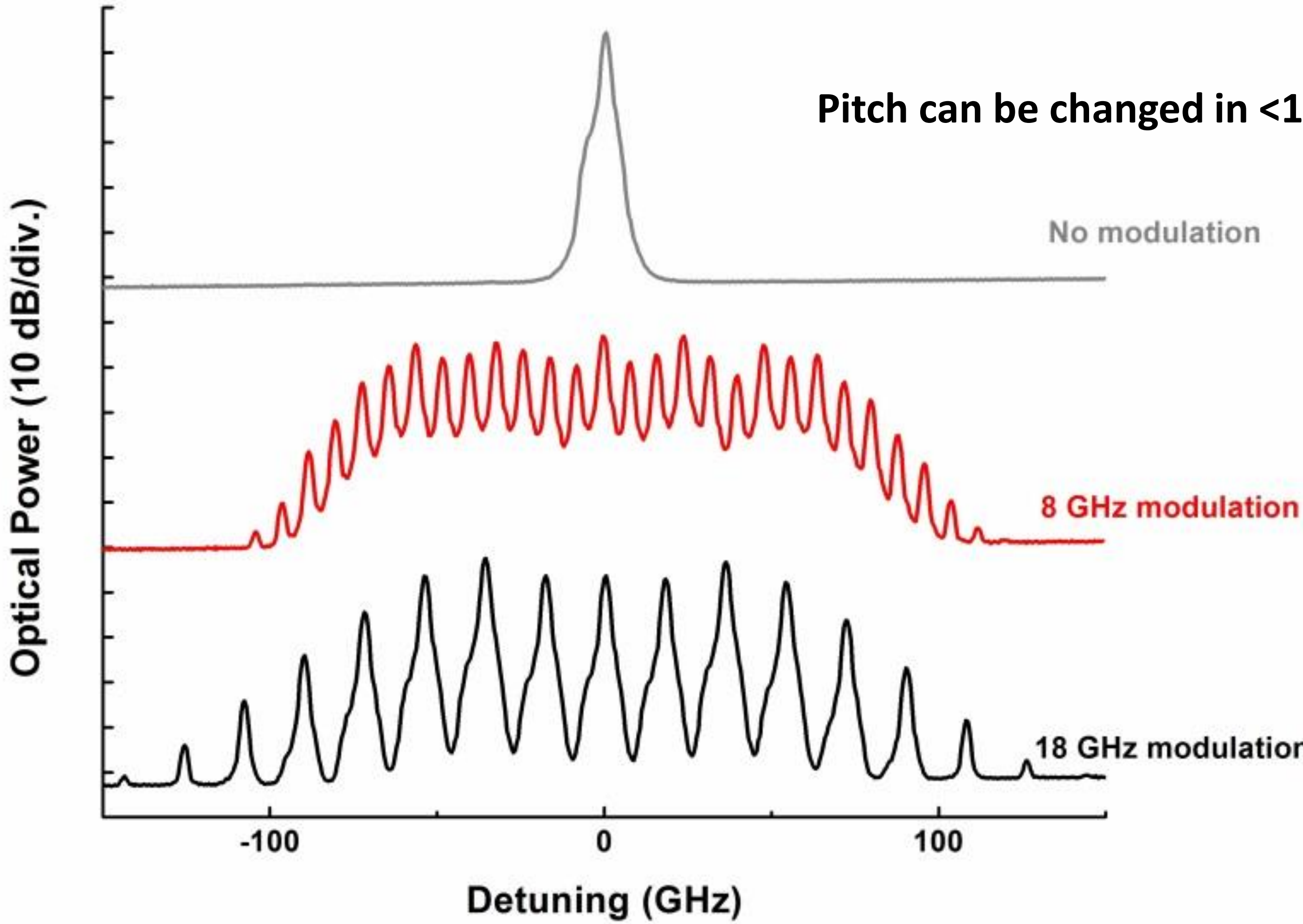


Dual-drive MZM allows for power-leveling of the comb

T. Sakamoto, et al., Electron. Lett., (2007).
D. A. Long, et al. Opt. Lett. (2014).

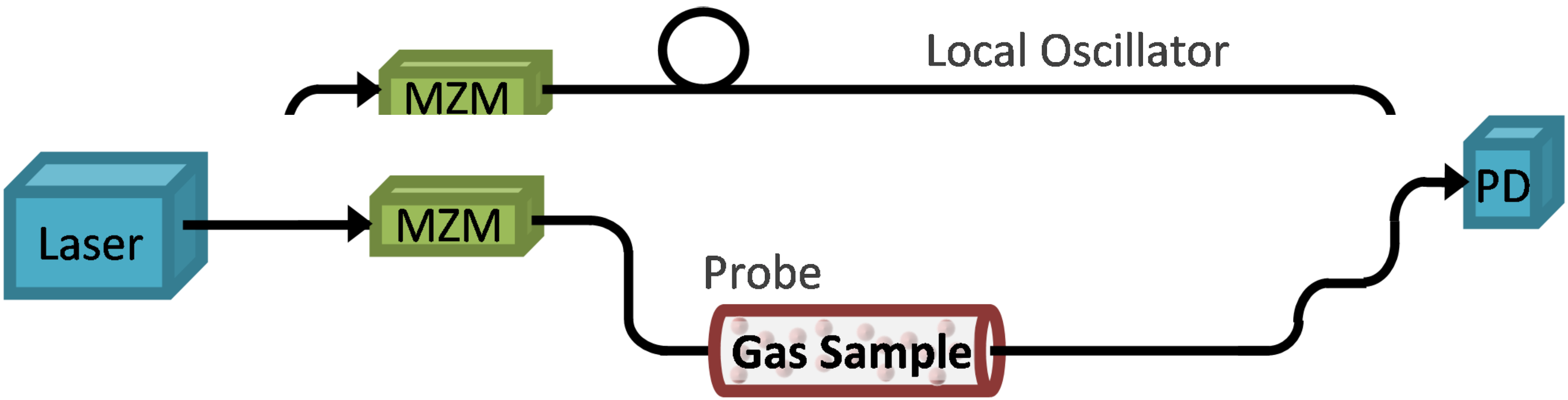
Variable pitch

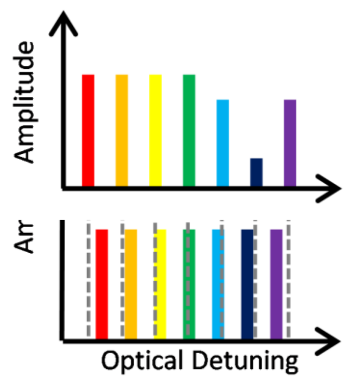
Pitch can be changed in <100 µs



D. A. Long, et al. Opt. Lett. (2014).

Multiheterodyne spectroscopy





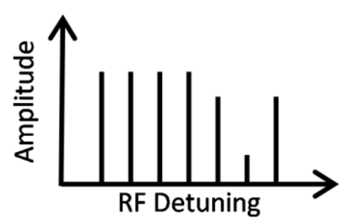
Probe

$f_{n,Probe} = nf_{\text{mod}} + f_0 + f_{\text{AOM}}$

Local Oscillator

$f_{n,LO} = n(f_{\text{mod}} + \delta_{f_{\text{mod}}}) + f_0$

Common mode (no need for phase locking)

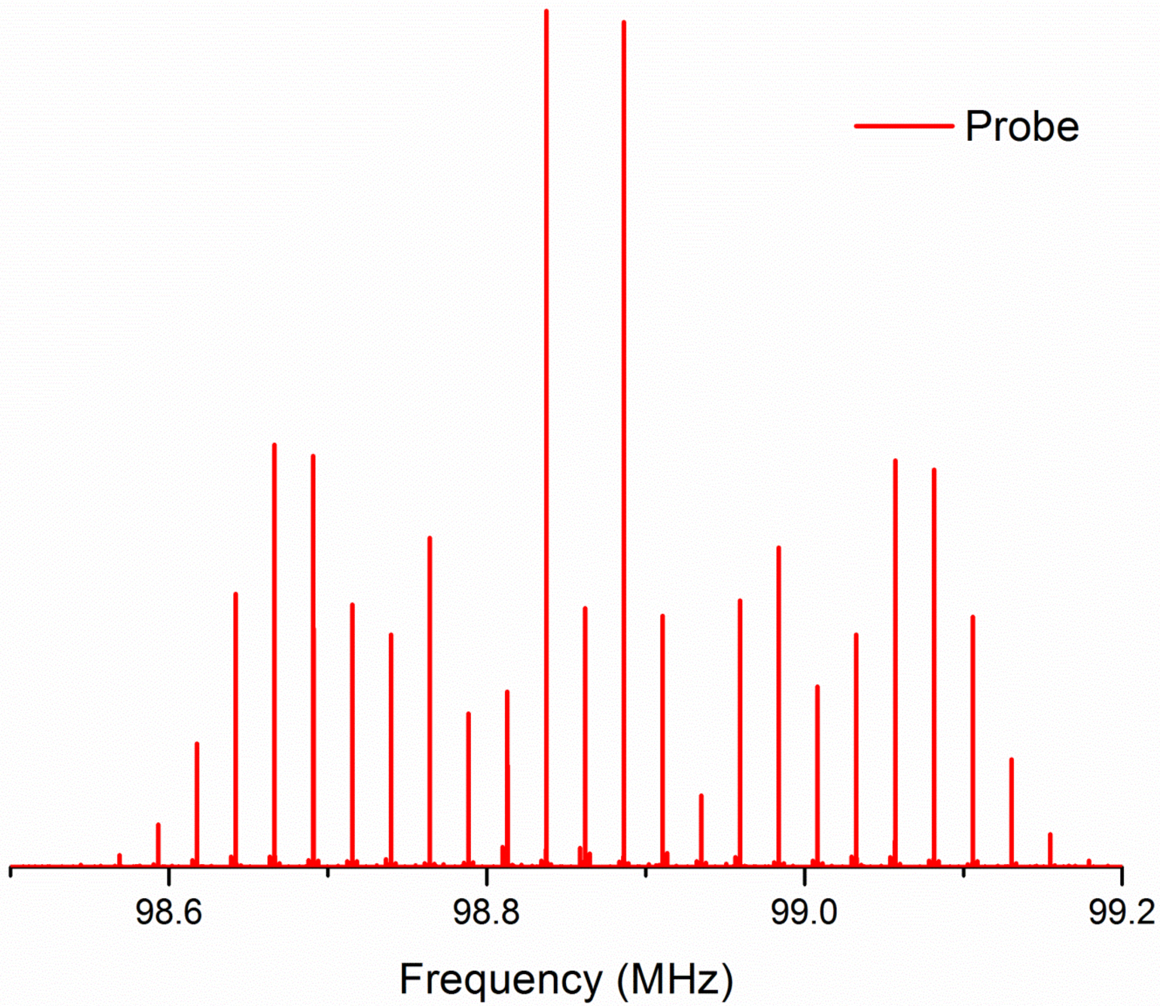


RF Heterodyne

$f_{n,RF} = n\delta_{f_{\text{mod}}} + f_{\text{AOM}}$

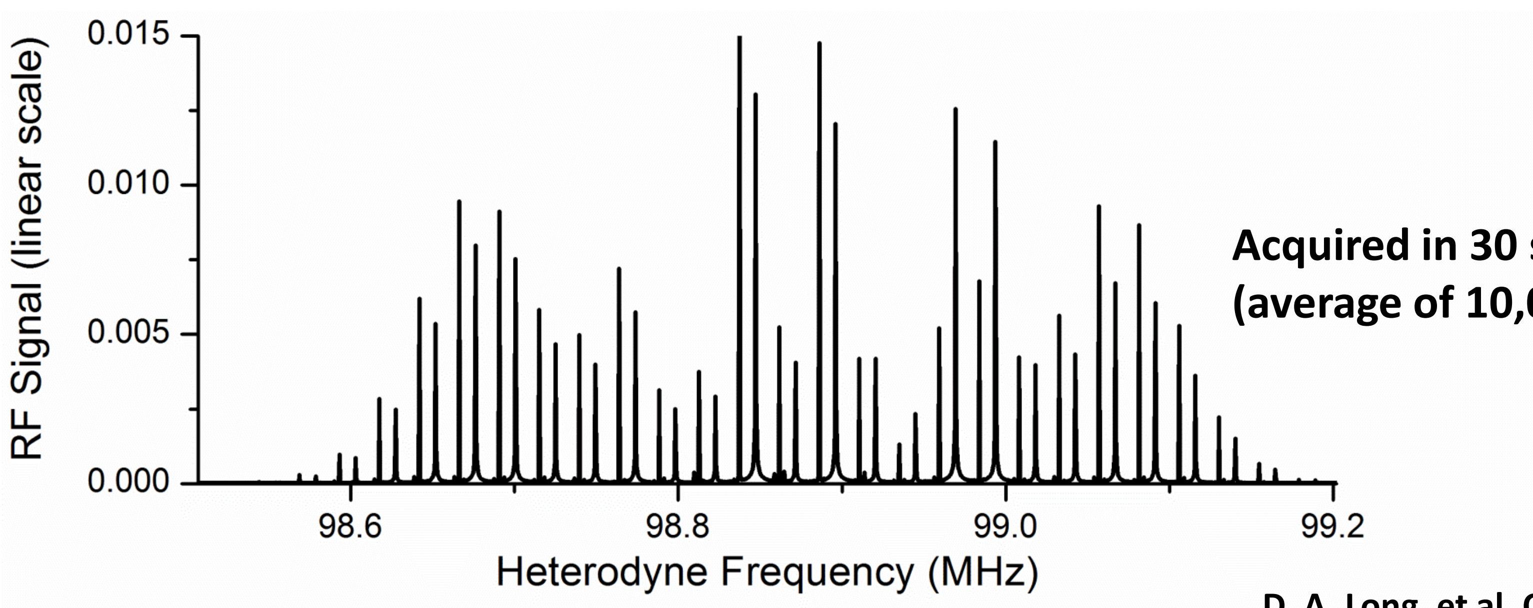
D. A. Long, et al. Opt. Lett. (2014).
D. F. Plusquellic, et al. US Patent Pending (2014).

Referencing



D. A. Long, et al. Opt. Lett. (2014).

Multiheterodyne spectra

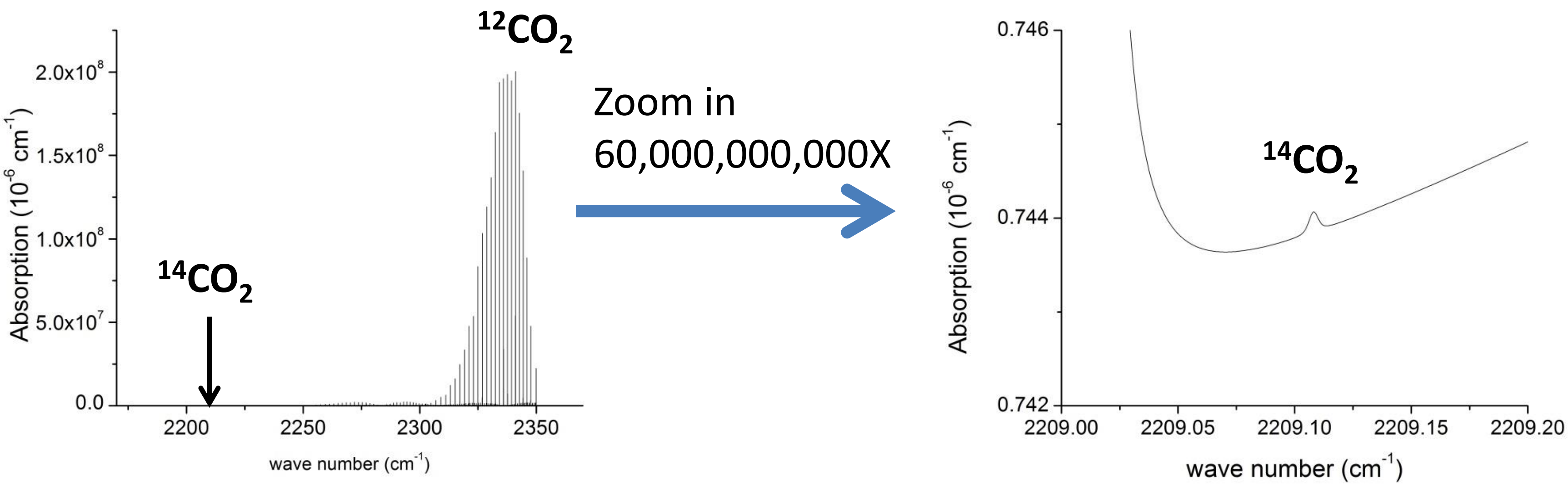


Acquired in 30 s
(average of 10,000 spectra)

D. A. Long, et al. Opt. Lett. (2014).

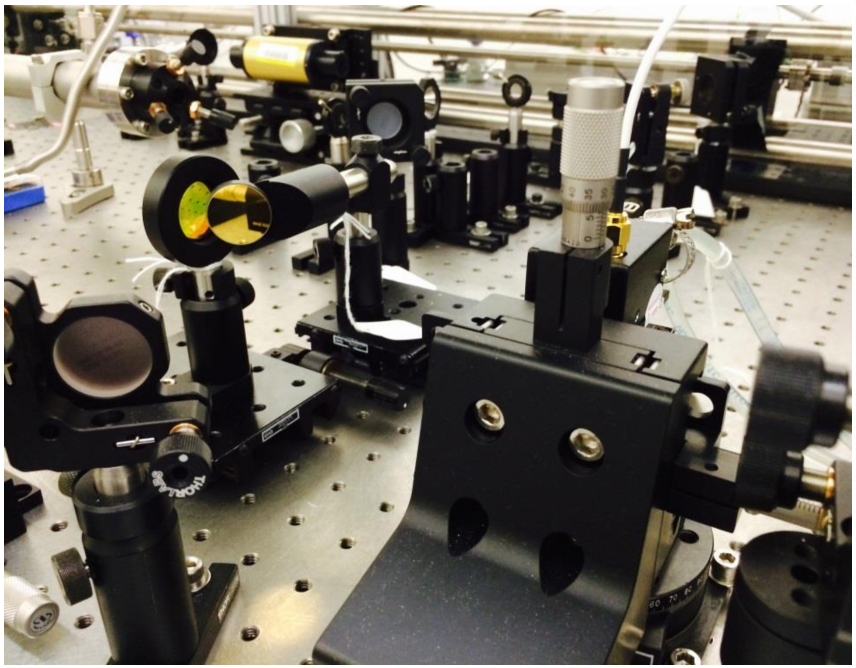
Where are we headed?

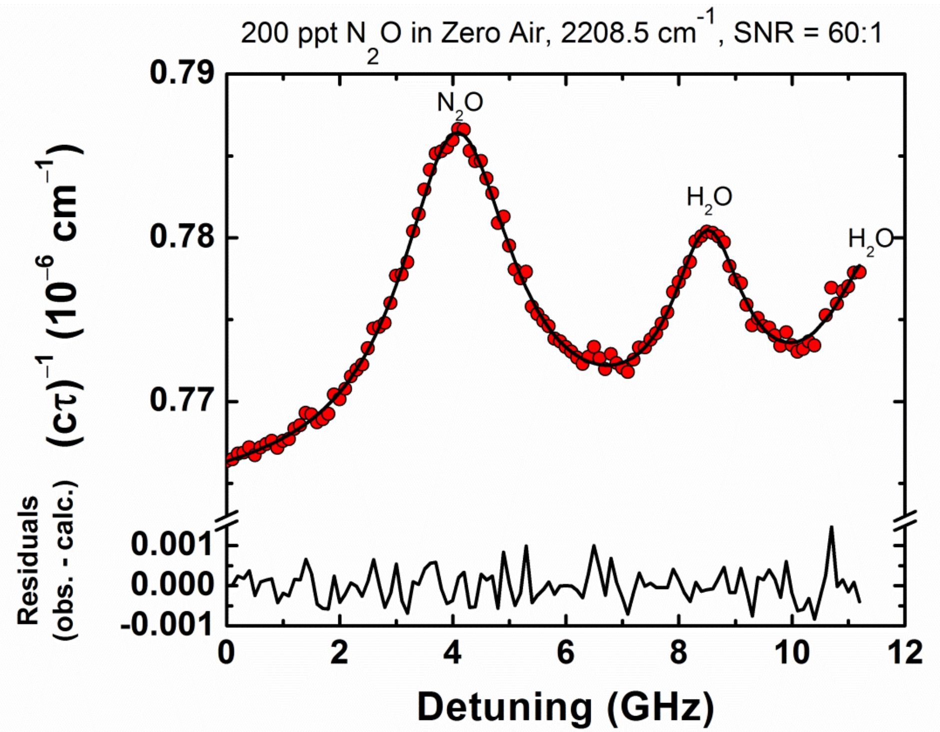
- **The mid-infrared**
- **Probing the strongest molecular transitions allows for the lowest detection limits**



Cavity ring-down spectroscopy in the mid-IR

- **Instrument is up and running!**





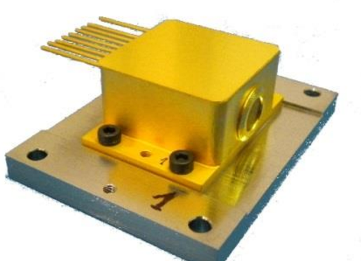


Image from Alpes Lasers

Detection limit of <u>3 ppt</u> for N_2O

Conclusions

- **Presented several new techniques for rapid, ultrasensitive detection of GHGs**
  - **Photoacoustic spectroscopy (PAS)**
    - **Relatively simply instrument allows for routine sensing**
  - **Frequency-agile, rapid scanning (FARS) spectroscopy**
    - **Use an EOM to step scan the laser frequency**
    - **Scanning rates limited only by the cavity response time**
  - **Heterodyne-detected cavity ring-down spectroscopy (HD-CRDS)**
    - **Make the measurement well above DC**
    - **Leads to quantum-noise-limited sensitivity**
  - **Multiheterodyne spectroscopy with EOM-generated optical frequency combs**
    - **Allows for multiplexed detection of several trace gases**
    - **Far lower costs and complexity than with femtosecond lasers**
    - **Inherently common-mode**

Acknowledgements

- Joseph Hodges, David Plusquellic, Adam Fleisher, Zachary Reed, Gar-Wing Truong, Szymon Wojtewicz, Katarzyna Bielska, Hong Lin, Qingnan Liu, Kevin Douglass, Stephen Maxwell, Roger van Zee
  - NIST

- NIST Greenhouse Gas Measurements and Climate Research Program

- NIST Innovations in Measurement Science (IMS) award